DRAFT – BNL Proposal to Conduct Accelerator R&D - DRAFT
for a Future U.S. Neutrino Physics Program
Brookhaven National Laboratory
October xx, 2005

[Version: October 7, 2005]

Executive Summary

This is a proposal submitted by Brookhaven National Laboratory (BNL) to the U.S. Department of Energy (DOE), Office of High Energy Physics (OHEP), to conduct ***Accelerator R&D*** focused on the improvement of accelerator systems and capabilities needed for effective realization of future accelerator-based sources of ***intense neutrino beams***. Our proposal emphasizes the most pressing R&D needs required by the ***'Super Neutrino Beam'*** concept identified in the 2004 Office of Science Future Facilities Intiative[1]. The proposed R&D work will be central to the future effectiveness of the U.S. Neutrino Oscillations Program using accelerator sources of neutrinos. We outline a program that is structured to evolve over a three-year period, indicating technical goals, requested OHEP support levels and staffing levels to meet these national objectives. The proposed R&D topics are described in detail in the Main Text sections below. A prioritized list of topics and proposed support levels is provided here.

Our 1st priority is directed to generic high-power, proton target and integrated target/horn meson-focusing systems R&D. This proposed R&D work will be needed by *any accelerator source* that proposes to advance the capabilities of the U.S. in future accelerator-based neutrino experiments. We also observe that, beyond the neutrino-less double beta-decay and high-precision reactor neutrino experiments currently under consideration for near-term approval, the future effectiveness of neutrino oscillation research will depend upon the development of Megawatt-class target sources and Megaton-class detectors, hence the need for the high power proton target and horn R&D. Our 2nd R&D priority is for development of *proton beam transport magnets* using high temperature superconductors, a development that will significantly reduce both construction and operating costs for a super neutrino beam program. Our 3rd priority is for the development of novel, *Fixed-Field, Alternating-Gradient* (FFAG) *conceptual accelerator designs* that could provide a less costly, high-power proton driver for neutrinos than the present superconducting linac approach. The potential applications of a successful FFAG R&D program extend beyond the improvement of future neutrino beam facilities into the regime of general application to new, high-power proton accelerators for a variety of new scientific applications. Our 4th priority is for the conceptual development of a *plasma lens focusing system* for a high-power proton target plus a low-duty-factor prototype. The optical properties and, more importantly, the radiation damage mitigation for this kind of focusing system, make this a very attractive R&D subject. The current prospects point to a probable success.

Although there were additional, compelling R&D projects and tasks that we considered adding to this proposal, we felt that the program presented here would address the most important accelerator R&D issues that need to be addressed for the future U.S. neutrino program.

We supply here, a Table of proposed Accelerator R&D projects listed in BNL's priority order.

Table of BNL Accelerator R&D Topics and Budgets by Fiscal Year

Project Name	BNL Priority	FY06 ($K)	FY07 ($K)	FY08 ($K)	Total ($K)
Target Materials & Target/Horn Integration	1	820	970	290	2080
High Temperature Superconducting Magnets	2	363	321	0	684
FFAG Accelerators For Neutrino Physics	3	351	487	385	1223
Plasma Lens R&D for a Super Neutrino Beam	4	200	200	200	600

We will seek an opportunity to discuss these ideas with DOE-OHEP in the near future.

[1] "Facilities for the Future of Science, A Twenty-Year Outlook", U.S. DOE Office of Science, Nov 2003.

Main Proposal

Introduction:

The Office of High Energy Physics has indicated that it plans to support Accelerator R&D needed to advance a national program of neutrino physics in the United States. Central to this program is the expectation that the future U.S. neutrino program will rely upon the construction of a megawatt-class proton driver to realize the DOE Office of Science's "Super Neutrino Beam" facility[1]. The Alternating Gradient Synchrotron (AGS) at BNL is the most intense source of multi-GeV (<30 GeV) protons in the world and represents a credible path to the required proton driver. Fermilab may also develop a credible and competitive plan for a proton driver. Our proposed R&D below will contribute effectively to either possible future U.S. accelerator path. We also note that the proposed Very Long Baseline Neutrino Oscillations (VLBNO) experiment will require maximal proton beam power plus a rugged and efficient pion focusing system to produce the required neutrino flux at the far detector, more than 2000 km from the production target. We present below a series of research and development topics that are focused on generic, accelerator-related topics that will provide high value to the AGS, or the Main Injector at Fermilab, or both. The chosen R&D topics explore new concepts and technologies that have the maximum potential for providing superior performance and cost effectiveness for an accelerator based neutrino program in the U.S., regardless of which accelerator facility is chosen as the proton driver and neutrino beam source. The goal is to identify the most effective technologies among the various alternatives (such as an FFAG versus a superconducting linac) within the proposed R&D period and position the U.S. to move ahead most effectively when construction is ready to commence.

Principal Investigators:

The Accelerator-related Neutrino R&D Tasks, described in some detail in the sections below, will be managed by the following Principle Investigators (PIs). All the proposed work will be performed by BNL staff members in the departments shown.

R&D Task	Principal Investigator(s)
Task 1 – Solid and Liquid Target R&D Studies	H. Kirk, Physics Department N. Simos, Energy Sciences and Technology Dept.
Task 2 – Target/Horn Integration R&D	N. Simos, Energy Sciences and Technology Dept.
Task 3 – High Temp. Superconducting Magnet R&D	R. Gupta, Superconducting Magnet Division
Task 4 – FFAG Accelerator R&D	A. Ruggiero, Collider-Accelerator Dept.
Task 5 – Plasma Lens R&D for Super Neutrino Beam	A. Hershcovitch, Collider-Accelerator Dept.

1.0 Target Materials and Target/Horn Integration:

I: High Power Proton Target R&D for Neutrino Physics Applications

There is a world-wide effort to design and implement "Proton Driver" primary proton beams in the multi-MW class that can generate powerful, intense secondary neutrino beams for use in future neutrino oscillation (and other) physics experiments. To realize this programmatic goal, significant technical challenges must be addressed before suitable *proton beam targets* can be developed. These issues include: 1) thermal management of the large target-heating generated by the interacting/showering proton beam; 2) radiation damage that alters material properties leading to possible degradation of target performance; and 3) generation of intense pressure (shock) waves that can lead to target destruction.

The BNL targetry R&D program has been organized and pursued in response to these recognized problems. The program includes a study of possible candidate target materials with a wide range of atomic-Z numbers. It also recognizes that different types of secondary beams have different optimal production characteristics. For example, neutrino beams resulting from the decay of fast pions benefit from low-Z targets, anti-proton production is enhanced with targets in the mid-Z range, and low-energy muon production is optimal when copious soft pions are produced with high-Z targets.

Solid targets have been investigated with a focus on the survivability of the targets. Materials which are resistant to fracturing and break-up due to the generation of intense pressure waves are being sought. This program entails the irradiation of candidate materials in order to evaluate their properties after prolonged exposure to radiation. The pace of the BNL targetry R&D needs to be intensified to meet the needs of the future neutrino program in a timely way, so we supply the present proposal and specific tasks related to neutrino physics applications of targetry R&D.

Technical Issues for Target Materials:

To provide a viable target system utilizing a multi-MW proton source (2-4 MW) for a super neutrino beam and/or a neutrino factory, a comprehensive R&D study is required. The study needs to focus on target material candidates that have the promise of both functionality and longevity under high-power conditions. While experience in operating accelerator targets of modest power is widely available, the uncertainties associated with a power of an order of magnitude higher are such that an R&D effort in which conditions approach those of the real target system is vital. Uncertainties that can only be resolved through experimental efforts are primarily linked to the radiation damage resistance of the target material expressed by its ability to withstand the induced thermal shock in its irradiated state while maintaining the key physical properties (thermal diffusivity, thermal expansion, etc.) that enable the entire target scheme to function in place for practical time durations of weeks to months without replacement

The problems presented by solid targets being exposed to intense proton beams has also led to a consideration of the merits of utilizing liquid targets for high-power sources. The Muon Collaboration, a national consortium that has been pursuing R&D for muon colliders and muon storage rings for a number of years, has developed a scenario for the production of intense low-energy muon beams based on immersing a high-Z liquid material (either Hg or perhaps a Pb-Bi eutectic) within a high-magnetic-field solenoid for the purpose of producing and capturing the soft pions generated when the proton beam interacts with the target. This effort includes a leadership role in the approved CERN experiment (nTOF11) to demonstrate the technical feasibility of a mercury jet target under conditions suitable for a Neutrino Factory. This work may also be applicable to "Super Neutrino Beams" a future DOE facility goal identified in the Office of Science document, "Facilities for the Future of Science"[2].

[2] "Facilities for the Future of Science – A Twenty Year Outlook", DOE Office of Science, Nov. 2003.

Task 1 - Solid and Liquid Target R&D Studies

Task-1.1 Solid Target R&D: Experimentally confirm that new alloys and composites, attractive for their mechanical and physical properties in the un-irradiated state and under consideration as baseline target options, retain these properties after being exposed to high power, high intensity proton beam. This task has two sub-tasks:

Sub-Task 1.1.1 Irradiation of target materials - The proposed work will extend the ongoing material irradiation effort at BNL to achieve radiation damage levels that are representative of the anticipated operational levels for both the super neutrino beam and the neutrino factory proton targets. The current materials study is exploring radiation damage (via intense proton exposures in BNL's BLIP radiation facility) in the following materials: two types of carbon-carbon composite (2D and 3D weave structures); new forms of graphite; new low-Z alloys (such as AlBeMet); so-called "super" alloys (super-invar and "gum metal"); plus titanium alloys and Vascomax (high-Z, high strength material). In the extension of the radiation studies proposed in this R&D sub-task, different grades of carbon-carbon composite (exhibiting variability in structure as well as density) will be exposed to high levels of radiation to allow for further studies of the radiation damage modification of its many attractive materials properties. At present, carbon-carbon composites appear to be the only solid-material option that can realistically support a >1 MW target system; as a result, carbon-carbon composite represents our chosen baseline material for the super neutrino beam target. In addition, we will explore the radiation resilience of the new alloys listed above for potential use in focusing horns (AlBeMet) or mid-Z targets considered for the neutrino factory initiative (super-invar, Vascomax, etc.). These irradiation studies will take place at various proton beam energies (i.e, 200 MeV at BNL's BLIP, 2 GeV at BNL's NASA line, 24 GeV at BNL's AGS and 120 GeV at Fermilab's Tevatron) so as to assess material damage at different primary proton beam energies.

Sub-Task 1.2 Post-irradiation materials study - The proposed work will focus on the resilience of target materials to cyclic proton beam shock and to changes caused by radiation damage in the thermal diffusivity, thermal expansion, resistivity and density reduction. All of the mentioned functions and properties are vitally important for a feasible target and horn system. Since recent experimental evidence suggests that some materials may recover from radiation damage by undergoing a special annealing process, we plan to explore how common this behavior is for the longer list of target materials considered. We also plan to carefully assess the compatibility of irradiated materials with potential target cooling fluids.

Task 1.2 - Liquid Targets R&D: The proposed task will experimentally confirm the concept of using high-Z liquid target materials in an intense proton beam. Prior R&D work in this area has been proceeding for several years under the Muon Collider/Storage Ring R&D program and could be important to the neutrino physics program of a future muon storage ring facility. Emphasis in the task proposed here will be placed on the ability to replenish the target after successive beam pulses while confirming that the dispersal of the liquid jet is manageable. This part of the R&D proposal will be to provide support for the approved target experiment, nTOF11 at CERN, an experiment designed to answer key questions concerning the performance of liquid-metal targets in a high-field magnetic field environment while being exposed to an intense proton beam pulse. The technical issues to be resolved include: trajectory and integrity of the liquid-metal jet in the magnetic field; explore the feasibility of 50 Hz operations; and the impact of μs proton bunch spacing on secondary particle production. We note that this task interacts with DOE's Muon Collider/Storage Ring R&D Program, in which BNL is a participant, and we would expect to discuss with OHEP how to integrate the tasks and goals of these two R&D aspects of the future U.S. neutrino program.

II: Horn/Target Integration R&D

High-Power Horn-Focused Neutrino Beams:

The use of pulsed, high-current magnetic lenses (“horns”) for fixed-target neutrino beam sources from proton accelerators has been the standard approach to providing wide-band neutrino beams for over thirty years. However, when the target power rises to the megawatt level, as will be the case for the Super Neutrino Beam envisioned in the DOE Office of Science “Facilities for the Future of Science” strategic plan[2], the technical challenges increase significantly beyond earlier experience. The feasibility, as well as the functionality, of an integrated target/horn system supporting the physics requirements of a multi-megawatt Super Neutrino Beam pose significant challenges that require a substantial new R&D effort. While the experience of running similar neutrino beam experiments at power levels an order of magnitude lower than those proposed can be of value in conceptualizing a target and horn system with the potential of operating at much higher power levels, this experience cannot be simply extrapolated to the design of a feasible and functional system at the megawatt power levels. This circumstance stems primarily from material limitations related to both target and horn, especially their ability to retain the key physical and mechanical properties for which they were chosen in the first place. The severe radiation damage conditions induced by the high-power proton beam, along with the cyclic thermal shock encountered with each current pulse, provide severe challenges to the operational goal of pulsing for the longest possible time before replacement of the target or horn components is needed. Attractive candidate materials from the physics performance perspective are certainly available but most of them lack crucial information on radiation-induced degradation of their key materials properties. Some of these candidates (i.e., graphite or carbon-carbon) have been exposed to high levels irradiation, but the radiation exposure data comes from reactor experience and is based on neutron rather than proton irradiation. This experience also derives from steady-state conditions in the absence of shock and rapid thermal cycling. Variations in the material response to different types of radiation are not yet measured experimentally.

Horn/Target Integrated System Performance Issues:

Performance limitations and/or failures of the integrated target/horn system of either past or running neutrino beam experiments (i.e., K2K horn, MiniBoone horn, NuMi target, etc.), operating at much lower power than what will be required for the super neutrino beam application, provide clear indications that technical issues remain and that that these will increase in severity as the required beam power rises.

The inability to reliably extrapolate the performance of low-beam-power experiments and operating experience into the design of the proposed multi-megawatt neutrino beam requires that the following R&D issues must be addressed to resolve the integrated target/horn system technical design and materials suitability questions:

1) Target Issues/Optimization:
- identification, design and proto-typing of an optimized target/horn configuration for parent pion capture in the desired wide-band neutrino beam, including robust and radiation-hard materials choices able to provide optimized pion collection for a multi-megawatt target/horn system;
- analysis of the optimal target configuration and materials for their physics application compatibility (including atomic numbers and densities) and the relationship of these to the inventory of radiation-hard materials or composites identified in the first task;
- analysis of the behavior of the target configuration and the expected cyclic beam-induced mechanical/thermal shock at the anticipated radiation-damage levels, and prediction of the longevity in service of the derived optimal target/horn system.

2) Horn Issues/Optimization

While the horn structure does not intercept the proton beam directly, it is still exposed to high levels of radiation from secondary particles and thus its ability to maintain the intended focusing function as radiation damage progresses is of primary importance. The ability of the horn material to maintain its resistivity as low as possible in the presence of progressive radiation damage is key to the selection and optimization of its design. This criterion is coupled with the requirement that serious degradation of the structural integrity of the horn (as it experiences radiation damage, thermal cycling due to electric current and proton beam heating, mechanical vibration and potentially corrosive cooling fluids) is strongly mitigated or avoided altogether.

In recent neutrino experiments, the failures of focusing horns that occurred earlier than anticipated, relative to their expected lives, point toward horn materials inability to resist radiation damage and to chemical corrosion degradation. Recent BNL radiation damage studies of horn materials (Fig. 1.1) showed that the material (even with a protective coating for fatigue resistance) experiences integrity degradation with modest levels of irradiation in a corrosive environment. At anticipated radiation damage levels that are an order of magnitude higher than current experience in the super neutrino beam era, the technical issue of getting the longest operational lifetime from the horn structure is of paramount concern.

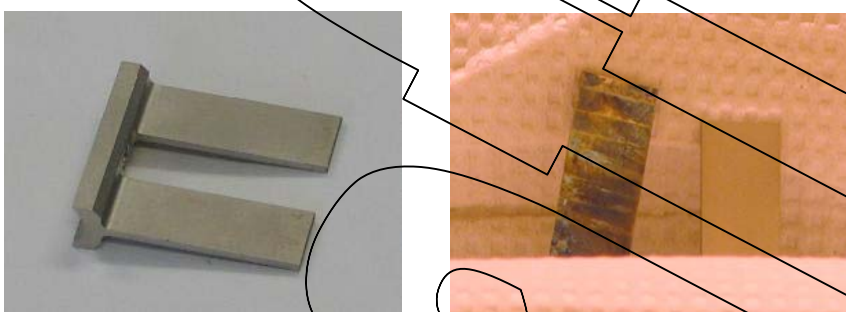

Figure 1.1: *Effects of modest levels of proton irradiation (~0.25 dpa) on nickel-plated aluminum of the NuMI Horn. Experiment was performed at the BNL BLIP facility with 200 MeV protons.*

In order to achieve the horn performance required by the super neutrino beam and to extend its operational life as much as possible, alternative materials options need to be considered in place of aluminum, the traditional horn body material. Significant technical progress in materials development has benefited other technical applications and now needs to be applied to horn and target optimization. Alloys such as AlBeMet, that exhibit favorable properties for horn use still lack radiation damage characterization. Such non-traditional alloys could provide a way to meet the technical challenges of a super neutrino beam horn with its associated multi-magawatt operating levels. The recent BNL materials irradiation study (while still at modest irradiation levels) produced results that favor the use of AlBeMet. However, further studies at higher irradiation levels are needed to establish the viability of this materials option.

3) Integral Target/Horn Challenges/Optimization

While the two primary elements of particle generation and focusing (i.e., target and horn) may be optimized to achieve their intended functions separately, they still need to be compatible in an integrated configuration. This is especially challenging because these two components need to be coupled in some respects of the operation (i.e., sharing cooling path) and be decoupled in others (i.e., remain electrically insulated) as seen in Figure 1.2. For both aspects (coupling or de-coupling) the beam power plays a pivotal role. The energy deposited in the target, as well as in the horn conductor, is directly proportional to the beam power as is the demand for a heat transfer path out of the integrated system. While the configuration geometry is similar to that of the low power neutrino experiments, the demand for heat removal capacity is about an order of magnitude higher under the same boundary conditions. Added to that is the expected degradation due to radiation damage of the material properties that control the flow of heat such as thermal conductivity or diffusivity; this is also expected to occur at much higher rates due to the higher beam power.

To achieve the performance required of the integrated system, the configuration as well as the materials that are involved, must ensure that both the heat transfer and the electrical insulation between the target and horn are maintained in satisfactory condition even under long-term irradiation. Experience from low power neutrino experiments is not directly transferable to the design of the proposed high power system and therefore dedicated R&D effort is necessary to address the issues. Our proposed work will address the following issues:

- The ability of helium gas flowing in the small annular space between the target and the horn inner conductor to remove heat deposited on the target. Helium gas is being considered to replace water cooling for several reasons: (a) the geometrical configuration to reach the optimal neutrino spectrum calls for an embedded target in the horn inner conductor that, in turn, has a very small diameter (~ 19mm). This geometry precludes the use of concentric annular spaces that allow coolant to flow past the surface of the target and never be in contact with the current flowing in the horn inner conductor. Helium gas represents the solution to the interface problem as long as it is capable of removing the target deposited heat at the rate required; (b) experience with water and its corrosive nature in recent experiments has not been positive. Protecting the horn surface from corrosion as well as the target surface from erosion will ensure a longer operational life. To assess the feasibility of helium cooling under such tight configuration, a dedicated heat transfer experiment needs to be performed while simulating the exact configuration of the proposed target/horn integration and materials as well as with the actual thermal loads anticipated.
- An assessment of the radiation hardness of special insulating materials that perform the role of horn/target coupling to endure the radiation damage expected over the maximum operating life of the integrated system.
- An assessment of the life expectancy of the integrated system subjected to the combined loading conditions. By utilizing radiation-induced material property changes, obtained by parallel efforts, simulations based on state-of-the-art software and modeling of the entire system are necessary to identify the weak points that may limit the life of the system. Since failure in one component, no matter how peripheral, would mean failure of the system as a whole, assessing the integrity under these high beam powers is vital. The NuMi experiment experience, in which a peripheral system failure caused significant beam downtime, is a reminder of the seriousness of the issue.

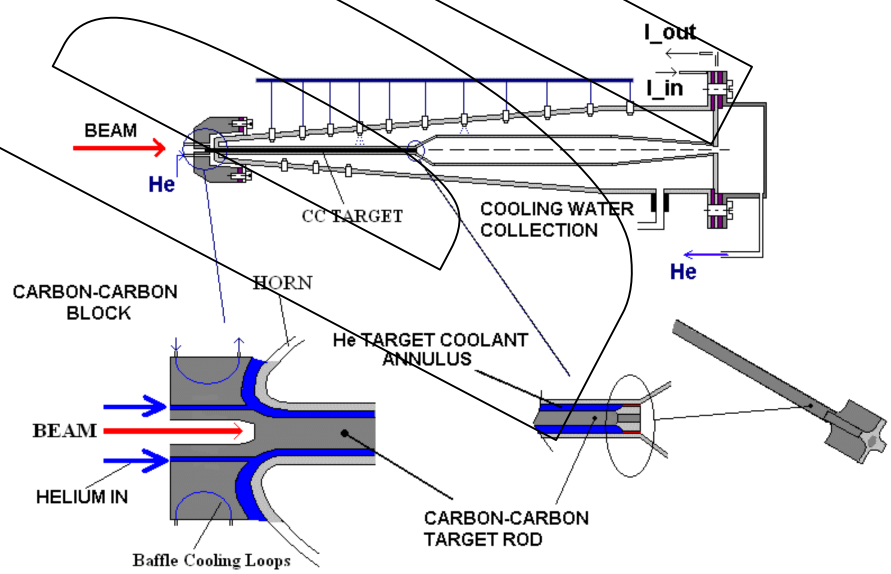

Figure 1.2: *Conceptual design of target/horn system for the BNL super neutrino beam*

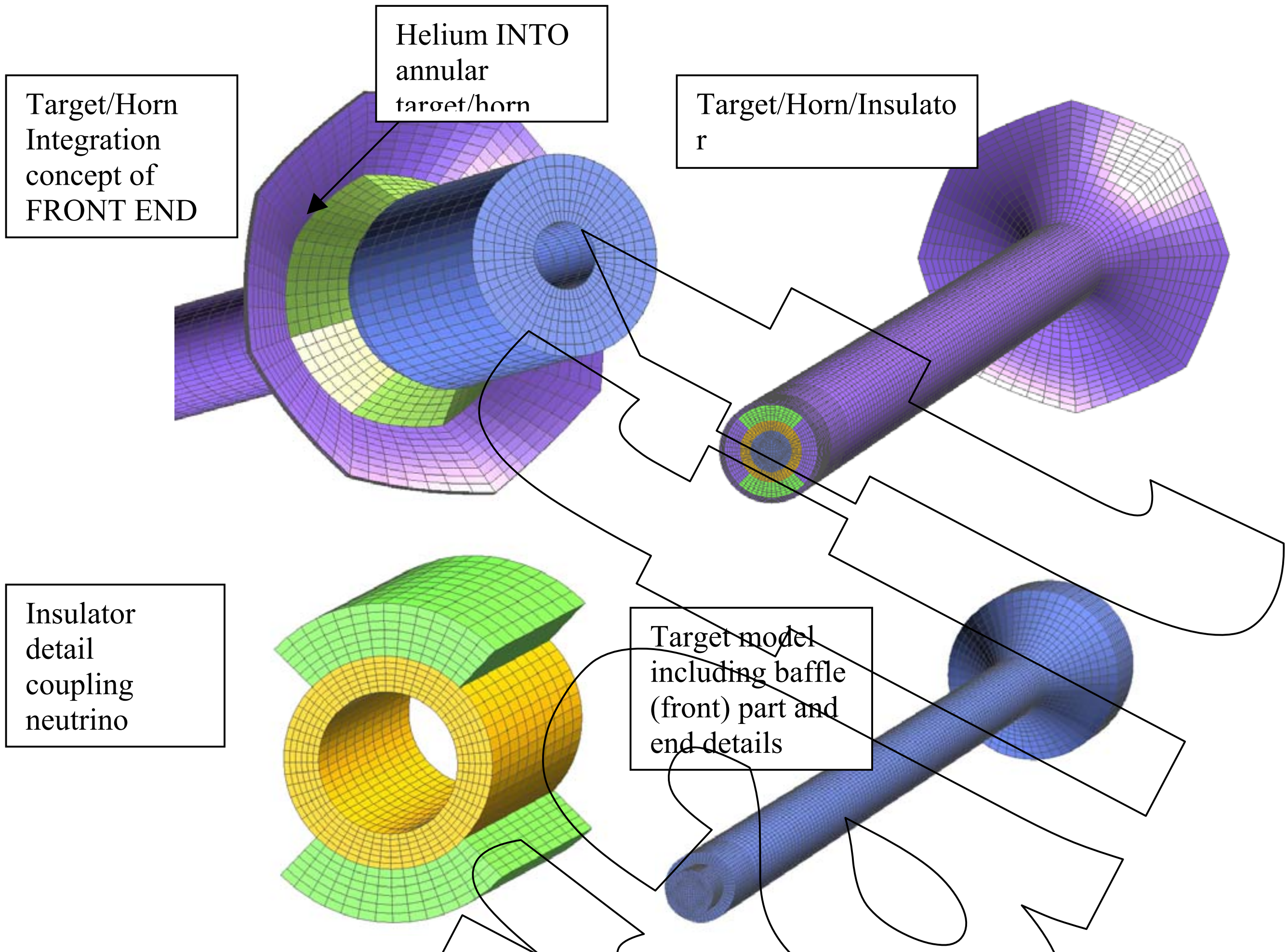

Figure 1.3: *BNL neutrino target/horn integration baseline model*

Task 2 - Target/Horn Integration R&D:

To address the above issues, the following R&D tasks are proposed to be performed over a 2-year period:

Task 2.1 - Conceptualize, simulate, design and test the critical section of the integrated target/horn system (i.e. target, horn inner conductor, insulator, and forced helium integration) for helium cooling verification and feasibility of the target/horn conductor coupling: To maximize the life of the two key components (target and horn) the option of using helium gas flowing in the annulus between the target and the inner conductor to remove the target thermal load will be explored. The thermal loads induced by the high power beam are about an order of magnitude higher than what target/horn systems have experienced in experiments to date. In addition, the low heat capacity of the inert gas proposed places further challenges in meeting the requirements. However, a proof-of-principle experiment showing that helium can be used in the proposed target/horn configuration, will eliminate far more serious issues associated with water cooling. The task will consist of three (3) subtasks, namely:

Sub-Task 2.1.1 - Helium cooling feasibility experiment: In a configuration simulating the horn inner conductor interfacing with the target (made of carbon-carbon composite or graphite) the ability of forced helium in removing heat deposited on the target inductively (similar to beam thermal load) will be tested and the maximum heat removal capacity of this scheme will be assessed.

Sub-Task 2.1.2 - Integrated target heating, helium flow and horn current pulsing experiment: Key to the long term survival of the system is the ability of the various components to withstand fatigue and induced vibrations from all three sources. Experimental testing of the proposed target/horn configuration will reveal potential weak spots thus allowing for the system modifications.

Sub-Task 2.1.3 - Testing of alternative material options: Explore other than the baseline materials for use as target, horn and insulators. Experimental verification of the erosion resistance of materials such as different grades of carbon composites and graphite to forced flow is of interest. In addition, assessment of electrical resistivity and corrosion resistance of materials other than aluminum as will provide potential alternatives for a horn with maximized life. Further, an experimental study, including irradiation, of different insulating materials that allow coupling between the horn and the target will provide much needed information on this key component of the system.

Task 2.2 - Optimize horn geometry to provide best neutrino flux:

Optimize the horn design on the basis of geometry and material that will, in conjunction with an optimized target, provide the best neutrino flux; study the feasibility of the optimal flux horn to be integrated with a target into a viable system.

Perform intense, high fidelity simulation studies of the super neutrino beam integrated target/horn system.

Sub-Task 2.2.1 - Simulate particle interaction with various target systems using transport codes and couple the hadronic analyses with thermo-mechanical simulations of the entire system.

Sub-Task 2.2.2 - Use both aspects of simulation (hadronic and thermomechanical) as well as irradiation data from a concurrent R&D to optimize the overall performance and design.

Sub-Task 2.2.3 - Focus on the simulation of the unique characteristics of the CC composite such as weaving of reinforcing fibers, anisotropic bulk structure and customization of fiber configuration to maximize important properties such as thermal diffusivity, erosion resistance and thermal expansion.

Sub-Task 2.2.4 - Identify the MW power capacity and life expectancy of the proposed target/horn scheme based on these comprehensive simulations. This is a very important task given that limitations in the target/horn system directly translate to limitations of the actual experiment. Understanding the limits of any proposed scheme (for this neutrino or any other experiment) in terms of useful life and power capacity is vital. Given that no proton driver to-date are capable of producing the powers proposed, the only path to assessing the system is based on simulations that analyze the exact system that has been benchmarked to powers that are achievable as of today.

Importance of Proposed R&D Studies to Future U.S. Neutrino Programs:

The proposed R&D target studies have wide appeal given that the target feasibility issues are common to all initiatives associated with multi-MW power accelerator drivers. All neutrino beams and neutrino factory initiatives fall into that category.

For the solid targets, the limitations arise from the fact that materials available to-date, including alloys and composites, may not be able to endure the kinds of demand these beam initiatives require. Advancements in material science hold part of the answer in solving material limitations, i.e., target resilience to beam induced shock. Comprehensive and systematic material irradiation studies are necessary in assessing whether new materials, alloys and composites can withstand the levels of radiation damage expected with long exposure to a multi-MW beam. This R&D is focused on covering a broad range of material Z and therefore increasing its relevance to a wide field of current and future initiatives for neutrino physics and beyond.

For the liquid target options where the target destruction is not the primary issue, issues associated with (a) the current lack of understanding of the behavior of conductive liquids in strong magnetic fields and (b) the thermodynamic processes that take place during beam-target interaction need both experimental and simulation-based verification. Through this R&D, both aspects are being proposed. Benchmarking of simulations that include magneto-hydro-dynamic and thermodynamic relations on the experimental efforts will provide the basis to assess how feasible a multi-MW liquid target is and what are its limitations.

The underlying statement regarding the value of high power target R&D is that all initiatives involving multi-MW proton beams have to address these target issues. Therefore, results of this R&D will serve any future neutrino beam and neutrino factory initiatives.

Further, with the ever-increasing demand for high power neutrino beams the pool of workable and realistic target/horn schemes reduces dramatically. This is due to the limitations of the materials, alloys and composites, available to-date, to endure the kinds of demands these beam initiatives require. This issue is common to all of present or future neutrino initiatives. Advancements in material science hold the key to solving individual component limitations, i.e., target resilience to beam shock or horn resilience to corrosion and electrical degradation. Solving the individual component issue does not, however, solve the issue as a whole because it is the integration of the system based on compatibility between components (target/horn/insulators/coolant) and functionality that is important. This R&D will address both the individual component integrity and the feasibility/functionality of the integrated system. By utilizing on-going and future planned studies of irradiation effects on materials as well as state-of-the-art simulations, areas where the proposing team has extensive expertise, limitations of the proposed neutrino beam initiatives stemming from the engineering side of the target/horn system as well as possible path toward these high powers will be identified. Results of this R&D will serve any future neutrino beam initiative.

Task 1 & Task 2 - Budgets and Staffing:

We provide a table with the associated R&D budget and costs for this increment to the BNL base R&D program, followed by the associated staffing by task.

Task 1 + Task 2 R&D Budgets by Fiscal Year

Budget Item	FY 2006 ($K)	FY 2007 ($K)	FY 2008 ($K)	Sum ($K)
Personnel[a]	680	720	240	1640
M&S (materials, irradiation charges, facility use, instrumentation, horn/target experimental set-up, etc.)	120	230	40	390
Travel	20	20	10	50
Totals	**820**	**970**	**290**	**2080**

Task 1 - High Power Proton Target R&D

Task 1.1: Solid Target R&D- H. Kirk and N. Simos, PIs (0.5 FTE each yr, FY06, FY07)
Physics Simulation Support: Scientific Staff (0.4 FTE each yr, FY06, FY07)
Post-Doc: TBD (0.5 FTE each yr, FY06, FY07) - Target shock simulations and data analysis
Work for Task 1.1 will be performed at BNL and FNAL
Task 1.2 - Liquid Target R&D - H. Kirk, PI
Post-Doc: TBD (0.5 FTE each yr, FY06, FY07) - Liquid target data acquisition; liquid target simulations
Grad. Student: TBD (0.5 FTE each yr, FY07; FY08) - Liquid target experimental data processing

Work for Task 1.2 will be performed at BNL & CERN

Task 2 - Horn/Target Integration R&D

Task 2.1 - Integrated target/horn simulations, Engr. and Exp. Helium Cooling Verification - N. Simos, PI (0.5 FTE each yr, FY06, FY07, FY08)
Grad. Student: TBD (0.5 FTE each yr, FY06, FY07, FY08): System simulation, modeling set-up, data acquisition and data processing
Mechanical Engineer (0.125 FTE each yr, FY07, FY8): Horn Mechanical Oversight
Electrical Engineer (0.125 FTE each yr, FY07, FY08): Horn and insulator testing set-up
System Tech (0.2 FTE each yr, FY08): TBD – System integration support
Work for Task 2.1 will be performed at BNL

Task 2.2: Horn geometry optimization – TBD, PI (0.5 FTE each yr, FY06, FY07)
Work for Task 2.2 will be performed at BNL

2.0 High Temperature Superconducting Magnets:

High Temperature Superconducting Magnet R&D for Neutrino Physics Application

Continued magnet R&D on cryogen-free super-ferric magnets (Fig. 2.1) based on High Temperature Superconductors (HTS) is proposed as a way to significantly reduce the operating cost and also potentially reduce the construction costs of the future Super Neutrino Beam Facility identified as part of the DOE Office of Science's 2003 Future Facilities Plan. The present proposal is built upon the recent success of the proof-of-principle HTS magnetic mirror model developed at BNL as part of the Rare Isotope Accelerator (RIA) R&D program [1]. Design concepts are being further developed so that these magnets, fabricated using commercially available HTS tape, become comparable in cost to room temperature water-cooled copper magnets requiring a field over 1.5 Tesla. Moreover, since HTS dipoles can generate significantly higher fields (~2.5T) than room temperature dipoles, this approach would also improve the technical performance of the targeting system, resulting in a more compact primary proton beam transfer line, thereby allowing a longer decay length and/or a shorter, cheaper tunnel.

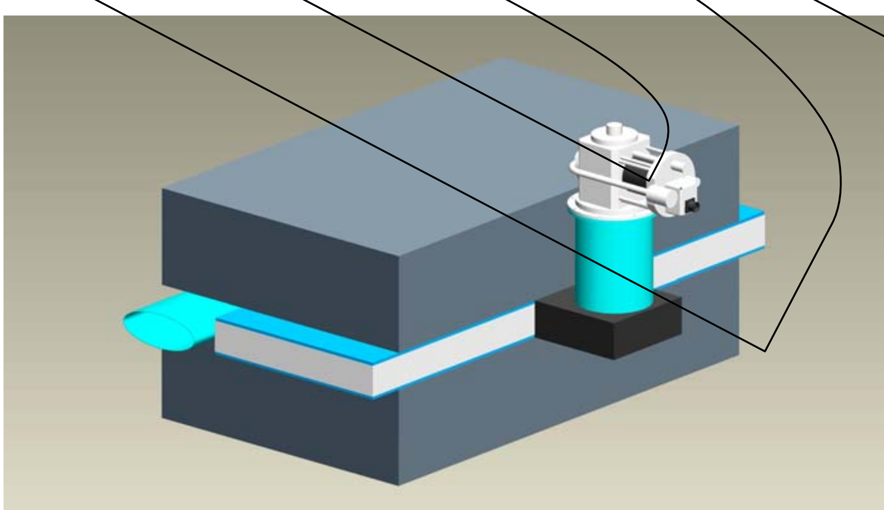

Fig. 2.1: *Conceptual design of HTS magnet with cryo-cooler for Super Neutrino Beam Line at AGS*

A primary proton beam transport constructed from such HTS magnets, operating at a temperature of ~35K, will be much more compact than room temperature magnets and will be cooled by plug-in cryo-coolers; hence, no cryogenic plant will be needed. HTS magnets will significantly reduce or potentially eliminate the beamline cooling water system. The magnets will operate below 300 amps, a factor of ten lower than the current required for room temperature magnets. The development of these magnets would not only reduce the operating cost (and perhaps overall construction cost) of the Super Neutrino Beam, either at Brookhaven National Laboratory (BNL) [2], or at Fermi National Accelerator Laboratory (FNAL) [3], but would also have a major impact in the wider field of large, high-field magnet applications. With energy costs likely to continue to rise significantly in the future, an energy efficient, HTS-based approach to high-current, high-field magnet systems could have significant spin-off potential beyond HEP applications. If this neutrino magnet R&D is successful, then the use of HTS magnets in beam lines and particle accelerators (requiring magnetic field in the range of ~1.5 T to ~3 T) will become widespread, replacing the water-cooled copper magnets that are expensive to build and operate. Having demonstrated a positive outcome with the Rare Ion Accelerator (RIA) HTS quadrupole, and being the only accelerator laboratory having this level of expertise with HTS magnet technology, BNL is in a unique position to carry this R&D to the stated level.

<u>Task 3 - Initial Design and Proposed Development</u>

The focus of the initial design studies, and of the proposed R&D, is BNL Dipole 3D144 [2]; however, this general concept can be applied to other dipole and quadrupole magnets. Dipole 3D144 is the largest magnet in the beam transport line, having a pole width of 153 mm and gap of 76 mm. The design field in the room temperature version is 1.55 T with a magnetic length of 3.73 m. In the case of HTS super-ferric magnets, the magnetic length can be reduced by increasing the design field.

H-shape and C-shape magnets (see Fig. 2.2 for magnetic design) have been considered as the part of this proposal. The two would have different cryostat and coil support structures. A C-shaped magnet is preferred because it is expected to produce lower cost magnets, primarily due to its single, simpler cryostat. A conceptual design of the cryostat for this C-magnet is shown in Fig. 2.3. The cryo-vessel (see picture on left) consists of top and bottom iron plates (light blue) plus a stainless steel frame on the side (gray). The coils, copper bars for heat transfer (dark brown), middle iron (blackish green) and other parts inside the cryo-vessel are shown in the right-hand picture. The fringe field outside the magnet could be reduced with additional shielding, if desired.

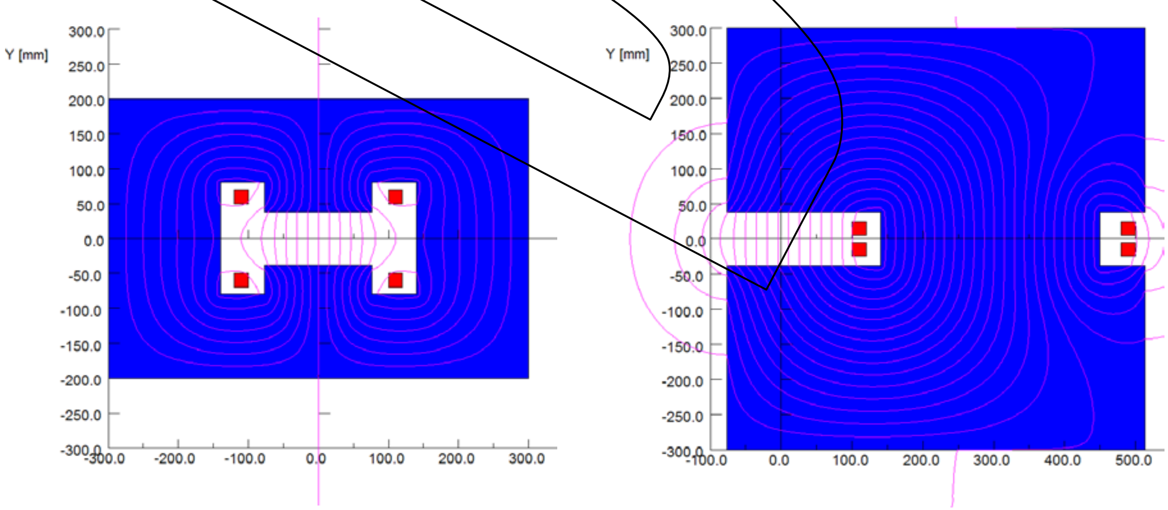

Fig. 2.2: *Magnetic designs (H-shape on left and C-shape on right) of dipole 3D144 for the neutrino beam line at AGS*

Detailed magnetic, mechanical and cryogenic studies will be carried out during the proposed R&D task to minimize the cost of the magnet. The actual determination of a particular design choice can be made only after this optimization phase has been completed. The magnetic design will be developed in such a way that, apart from producing magnets with the desired field uniformity in the aperture, the design also minimizes the maximum field and the vertical component of the field on the conductor. Unlike the case of conventional low temperature superconductors (LTS), the currently carrying capacity of HTS has significantly different values depending on whether the direction of field is parallel or perpendicular to the surface of the conductor. The cryogenic design will be developed such that the heat leak is minimal and the magnet can be cooled efficiently to the ~35 K operating temperature with a single-stage cryo-cooler within a reasonable amount of cool-down time. The maximum variation in temperature in HTS coils can be allowed to span a few degrees rather than the few tenths of a degree required by magnets fabricated using conventional low temperature superconductors.

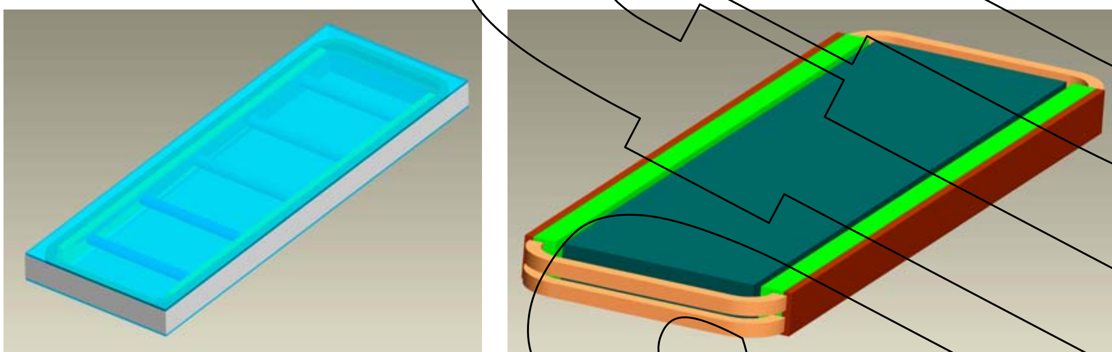

Fig. 2.3: *Conceptual design of cryo-vessel (left), with inside components (coil, cooling copper bar, iron, etc.) on right.*

<u>Major Benefits for Neutrino Beam Applications</u>

The proposed HTS energy-efficient magnet technology would significantly reduce the operating cost of the primary proton beam transport line. It may also provide an enhancement in the performance by allowing a shorter primary beam transport line, or a longer decay channel (hence a large neutrino beam intensity) or both.

As an example, the primary beam transport line for the Neutrino Super Beam Facility at BNL will use a significant number of dipoles (the total bend is about 1/4 of that of the AGS ring) plus significant numbers of quadrupole magnets. The present proposal is based on conventional room-temperature magnets. With the rapid AGS cycle rate, the beamline will operate continuously at full excitation and has been estimated to consume ~3MW of power (~$2K/day) or about $250K for a nominal 5 month run at current prices. HTS magnets will reduce construction costs as a result of the shorter tunnel, no cooling water system, a low-power magnet power supply system, etc.

First-generation high temperature superconductors (BSCCO) are now commercially available in large quantities. The cost of HTS wire per ampere per meter has been continuously decreasing over time. Moreover, a major milestone has been achieved in the demonstration of the industrial manufacturability of the second-generation superconductors (YBCO). This result will have the far-reaching impact of a large reduction in conductor cost as the 2nd generation wire does not require silver as a major component of the conductor composition. The projected reduction in cost from the manufacturer is a factor of three to five within the next five years.

Even with the present market value of the 1st generation superconductor, the expected cost of a HTS magnet system appears to be comparable to that of room temperature magnets. For example, the cost of conductor for the largest and most powerful dipole magnet in the beam line (3D144) will be ~ $50K even with the current price of HTS. This is about 1/3 of the total estimated cost of the equivalent room temperature magnet.

Personnel and Schedule

Following BNL persons will be involved in carrying out the proposed R&D project:

1) R. Gupta (Scientist), PI
2) K.C. Wu (Cryogenic Engineer)
3) P. Kovach (Design Engineer)
4) J. Schmalzle (Mechanical Engineer)
5) G. Jochen (Technician)
6) R. Ceruti (Technician)

The design work on a short model magnet will be completed in the first fiscal year (FY2006). In addition, conductor will be purchased and the first coil will be wound and tested in liquid nitrogen. Rest of the coils will be wound and individually tested in the middle of fiscal next fiscal year (FY2007). The complete magnet will be built and tested with cryo-cooler by the end of FY2007.

Task 3 Budgets

A two-year R&D Task 3 is proposed to design, build and test a stand-alone model of dipole magnet 3D144. The total cost of this project will be $684K. The major focus of this R&D will be the development of designs that would reduce the HTS magnet cost. A longer-term (~five years) goal of the HTS magnet program at BNL is to demonstrate a design that allows the fabrication cost for a practical HTS magnet to become comparable to an equivalent room temperature magnet with a field of 1.5 T or above. The proposed project will produce a proof of principle 3D144 dipole magnet that would technically and economically validate the above premises. This HTS technology could also be used in other transfer line magnets where found economically attractive.

The breakdown of the above Task 3 budget is given below:

Task 3 R&D Budgets by Fiscal Year

Budget Item	**FY 2006 ($K)**	**FY 2007 ($K)**	**FY 2008 ($K)**	**Sum ($K)**
Scientific Effort (0.25 FTE yr each FY)	55	57	0	112
Engineering Effort (0.25 FTE yr each FY)	48	50	0	98
Technician/Designer Effort (0.5 FTE yr each FY)	160	164	0	324
Materials	100	50	0	150
Totals	**363**	**321**	**0**	**684**

References:

[1] R. Gupta, et al., “Test results of HTS coils and an R&D magnet for RIA”, presented at the 2005 Particle Accelerator Conference at Knoxville, Tennessee, May 16-20, 2005.

[2] The AGS-Based Super Neutrino Beam Facility Conceptual Design Report, Editors: W.T.Wang, M. Diwan and D. Raparia, BNL-73210-2004-IR, October 8, 2004.

[3] Conceptual Design for the Technical Components of the Neutrino Beam for the Main Injector (NuMI), J. Hyden, et al., FERMILAB-TM-2018, September 1997.

3.0 FFAG Accelerators for Neutrino Physics:

Fixed-Field Alternating Gradient Accelerators for Neutrino Physics Applications

To implement a comprehensive program of research on Neutrino Oscillations it is essential to provide a Proton Driver capable of delivering an average beam power upwards of 1 MW at a workable proton beam energy and repetition rate. The *Proton Driver* is a source of high-intensity primary protons that, by impinging on a target of highly radiation resistant material, generates pions that decay into neutrinos and muons. This high-intensity beam has been designated the *"Super Neutrino Beam"* in DOE's "Facilities for the Future of Science" plan of November 2003. To achieve the most cost-effective approach to the Proton Driver, we believe that Fixed-Field Alternating-Gradient (FFAG) accelerators offer the brightest promise for the Super Neutrino Beam application, provided the essential accelerator R&D is pursued in a timely way. BNL proposes to pursue some of the critical items for this R&D mission in the paragraphs below.

Horn-focused neutrinos born in the decay volume of the super beam are transported over a long distance to perform the so-called (Very) Long Neutrino Baseline Experiment in a large neutrino interactions detector located far from the beam source. The muons from pions in the super beam can also, themselves, decay to generate electrons and more neutrinos. Taking advantage of their relatively long lifetime, it is also possible to collect these secondary decay muons into beam accumulator and cooling devices, from which they are extracted and accelerated to high energies in a sequence of Super-Conducting Linacs (SCL) and/or (FFAG) accelerators. The muons are then stored in storage rings where they decay to generate neutrinos aimed toward the large neutrino detector. This latter beam forming system is commonly referred to as a Neutrino Factory. Thus the neutrino physics experimental program may deal with a Super Neutrino Beam and perhaps later, a Neutrino Factory. In either case, the large flux of neutrinos required can be obtained only with a Megawatt-class Proton Driver.

Brookhaven National Laboratory (BNL) is investigating an Upgrade [1] of the Alternating Gradient Synchrotron (AGS) complex to boost the average proton beam power to 1-2 MWatt, about an order of magnitude over the present performance, at a proton beam energy of 28 GeV and repetition rate of 2.5-5.0 Hz. This powers a Super Neutrino Beam to be launched over a distance of about 2,500 km. For this purpose, a new injector to the AGS could replace the existing Booster. The present conceptual solution is a 1.2-1.5 GeV SCL [2], based upon the just-completed Spallation Neutron Source (SNS) at ORNL. A second solution could be a 1.5-GeV FFAG injector located in the AGS tunnel [3]. This solution is expected to be more economical but requires substantial R&D. At the same time, BNL is also directly involved in the international collaboration for the study of Neutrino Facilities at a generic accelerator site. In this case, the required Proton Driver could also be made of FFAG accelerators as recently proposed [4], since these compete well with SCL and Rapid-Cycling Synchrotrons (RCS) in cost and performance. One should also note that acceleration of muons to high energy, prior to their decay into neutrinos, can also be achieved in a sequence of FFAG accelerators. BNL is already involved in the conceptual study of design and performance of FFAG accelerators. As a result, BNL offers substantial expertise and motivation to advance the national program in accelerator R&D for neutrino physics. This R&D is also important for a much wider scope of accelerator applications.

FFAG Accelerators have the capability to accelerate charged particles over a large momentum range, and have the feature of constant bending and focusing fields. Thus magnets do not need to be ramped and particles can be accelerated relatively fast at the rate given by the limitation of the accelerating field from RF cavities placed in proper location between magnets. FFAG accelerators are thus conceptually placed between SCLs, with which they share the fast acceleration rate, and RCSs, as they allow the beam to re-circulate over fewer revolutions. They are similar to Cyclotrons but also take advantage of alternating focusing and bending for a more radial compact geometry, and free themselves from the rigid relation between RF frequency and orbit path length.

Two lattice configurations and magnet arrangements for FFAG accelerators have been proposed. The first is the *Scaling Lattice* that has the advantage of constant orbit parameters across a large momentum aperture but at the cost of high bending fields, large magnet aperture and a limitation on available drift space. This lattice has been experimentally demonstrated at KEK with a pair of FFAG proton rings that have been commissioned [5]. Moreover, several projects are now being proposed in Japan utilizing this principle. The second lattice configuration is the *Non-Scaling Lattice* where orbit parameters vary considerably across the momentum aperture, but with the benefit of lower bending fields, smaller magnet aperture and allowance for more drift space. The engineering and construction of a FFAG Accelerator based on this principle are greatly simplified and also expected to be more economical. Yet there is the concern of the beam stability when crossing a large number of resonances, some linear and others not, some driven by errors, misalignment and magnet imperfections, and others that appear to be structural. A *Non-Scaling* FFAG Accelerator has never been practically demonstrated. Yet several studies have been recently made on possible applications utilizing such a lattice, not only for the acceleration of muons, but also of protons, namely: AGS Upgrade, Proton Driver for Neutrino Factory; a green-field 10-MW Proton Driver at 1 GeV [6] for continuous neutron production, energy production, waste transmutation, etc.; and Medical Accelerators. In the design of these projects novel ideas have also recently been proposed. For instance, it is desirable to flatten the tune variation with an *Adjusted Field Profile* [7, 8] for a CW mode of operation [9] and for a better tuning and operation mode [10]. The concern of multiple resonance crossing in the case of proton beams is to be coupled to the longitudinal beam dynamics, requiring a fast frequency-varying RF cavity system; we also note that the presence of space-charge forces at injection may still be significant despite the fast rate at which the region of relevance is traversed. Clearly, a robust R&D program is necessary to better determine the suitability of FFAG accelerators in these areas that bear directly on the future U.S. neutrino experimental program.

<u>Task 4 - FFAG Accelerator R&D</u>

Here we propose Task 4 R&D FFAG studies over a three-year period beginning with FY 2006. The main goal of the study is to establish the feasibility of FFAG accelerators for the neutrino experimental program, to outline the merits by comparing them to other accelerator architectures (RCS and SCL), and to solve outstanding issues in beam dynamics, design and engineering. In particular, we propose to:

1) look in detail at the design procedure, design optimization and numerical tracking of both transverse and longitudinal motion;
2) investigate the effects of space-charge at injection;
3) determine the formation of Beam Halo during Injection and Acceleration and the latent beam loss that need to be controlled to avoid activation of the ring components;
4) explore alternative FFAG designs, namely Linear-Gradient versus Adjusted Field Profile, Doublets versus Triplets, etc. etc.;
5) investigate magnet design by designing prototype magnets with required *Adjusted Field Profile* and/or asymmetric quadrupole field;
6) investigate tolerances of magnet misalignment and gradient errors and their effects on beam stability and losses;
7) study disruptive effects caused by crossing linear and non-linear resonances, whether error driven or of intrinsic nature;
8) design an RF cavity system for acceleration over a large frequency range and study RF capture at injection and acceleration;
9) investigate the possibility of continuous beam acceleration (CW mode of operation) with the method of *Harmonic Jump*;

10) explore the feasibility of an Electron FFAG model of an energy and intensity range to effectively simulate low-energy proton beam behavior;
11) estimate the cost of each of the conceptually designed facilities;
12) extend the investigation to more general and innovative FFAG studies.

The Task 4 study will mainly focus around the design of the 1.5-GeV FFAG as the new injector for the AGS Upgrade. But the results will also be applied to the conceptual design of the Proton Driver for a Neutrino Factory, since they both share the same technical issues. Though most of the 12 topical elements listed above can be studied simultaneously, a certain time sequence is nonetheless necessary as outlined in the time schedule here:

Tasks / FY	2006	2007	2008
1.	XXXX		
2.	XXXX		
3.	XX	XX	
4.	XXXX		
5.		XXXX	
6.		XXXX	
7.		XXXX	
8.		XXX	X
9.		XX	XX
10.		XXXX	XXXX
11.			XXXX
12.			XXXX

At the end of each Fiscal Year a summary report will be issued that contains the results of each of the 12 topical studies. At the end of the three-year period of R&D, a conceptual Design Report of the 1.5-GeV FFAG for the AGS Upgrade will be delivered. At the same time, although with lower priority and reduced size, reports will also be prepared for the Proton Driver within the Neutrino Factory context.

Task 4 Budgets

Our estimate of the cost to conduct this program of R&D for the FFAG accelerator studies is summarized in the following table (in 2005 dollars, fully burdened). Most of the cost is for labor. The amount allowed for material is to perform two important R&D experiments: (1) Practical demonstration that RF cavity ferrite can be swept at the required rate and frequency range, and (2) Design and construction of a FDF magnet triplet according to specification and with required field profile. Alessandro Ruggiero will be the Principal Investigator for this work.

Task 4 R&D Budgets by Fiscal Year

Budget Item	**FY 2006 ($ K)**	**FY 2007 ($ K)**	**FY 2008 ($ K)**	**Sum ($ K)**
Accelerator Physicist (1 FTE for each of 3 years)	319	338	353	1010
RF Engineer/Physicist (0.25 FTE FY 2007 only)	0	63	0	63
Mechanical Engineer (0.25 FTE FY 2007 only)	0	54	0	54
Total Personnel Costs	319	455	353	1127
Travel	20	20	20	60
Computing	12	12	12	36
Totals	**351**	**487**	**385**	**1223**

References

[1] AGS Super Neutrino Beam Facility, (NWG Report-II), Editor D. Raparia. BNL 71228 (Informal Report), April 2003.

[2] A.G. Ruggiero, "Review of Options for the SCL for the AGS Upgrade", BNL Internal Report, C-A/AP/#151. April 2004.

[3] A.G. Ruggiero, "1.5-GeV FFAG Proton Accelerator fore the AGS Upgrade", Invited Talk to EPAC-04, July 6-11, 2004, Lucerne, Switzerland.

[4] A.G. Ruggiero, "FFAG Accelerator Proton Driver for Neutrino Factory", Invited Talk to NuFact 05, Frascati (Rome), Italy. June 21-26,2005.

[5] S. Machida *et al*., "Commissioning of 150 MeV FFAG Synchrotron", Proceedings of EPAC-04, July 6-11, 2004, Lucerne, Switzerland.

[6] A.G. Ruggiero, "A 1-GeV 10-MWatt Proton Driver", Invited Talk to ICFA-HB2004 Workshop, October 18-22, 2004, Bensheim, Germany.

[7] A.G. Ruggiero, "Adjusted Field Profile for the Chromaticity Cancellation in a FFAG Accelerator", Proceedings of ICFA-HB2004 Workshop, October 18-22, 2004, Bensheim, Germany.

[8] A.G. Ruggiero, "Revision of the Adjusted Field Profile Estimate Criterion", BNL Internal Report, C-A/AP/#208. March 2005.

[9] A.G. Ruggiero, "CW Mode of Operation of a Proton FFAG Accelerator", BNL Internal Report, C-A/AP/#xxx. March 2005.

[10] A.G. Ruggiero, "Design Criteria of a Proton FFAG Accelerator", Proceedings of the FFAG'04 Workshop, October 13-16, 2004, KEK, Tsukuba, Japan.

4.0 Plasma Lens R&D for a Super Neutrino Beam:

The Plasma Lens as a Neutrino Beam Focusing System

A key requirement for a successful future neutrino program will be a very high-power (Megawatt-class) high-energy proton beam source, together with a very efficient pion-focusing system downstream of the primary production target. We assert that a ***plasma lens*** would be ideal for this purpose but the associated plasma lens technology will require substantial R&D to meet the neutrino beam application requirements.

To maximize the flux of neutrinos into an experimental neutrino detector located far from the beam source, as is required by a Very Long Baseline Neutrino Oscillation (VLBNO) experiment, the maximum number of high-energy pions from a primary proton target must be captured and magnetically focused into a directed beam before they decay into muons and neutrinos in the decay region of the source. Consequently, an ideal pion focusing and capturing lens should possess the following characteristics for maximizing neutrino beam signal at the detector:

1) very large axial electrical currents (Mega-amps) must be generated and sustained;
2) magnetic fields generated by these currents should capture the largest number of parent pions;
3) the lens medium should have lowest density possible to minimize pion absorption and scattering;
4) the lens must endure high mechanical and thermal stresses caused by high currents and EM fields;
5) the lens must survive prolonged exposure to radiation;
6) the lens should minimize neutrino background during anti-neutrino beam runs (signal purity);
7) a cost-effective, power-efficient lens is desirable.

A plasma lens offers many advantages over other focusing methods. Current levels of tens of mega-amps are carried routinely in some plasma devices, while current levels in conventional horns and lithium lenses cannot exceed a few hundred kilo-amps. In addition to be able to support larger currents than other lenses, plasma lenses can have their discharge profiles shaped for optimized pion capture. Unlike the presently considered horns, plasma lenses can capture and deflect pions with velocities that are at very small angles to target axis. In plasma lenses, current is carried in low-density ionized gases, while in other lenses the current is carried in solid matter or in liquids. Except for a couple of small electrodes, the bulk of a plasma lens is essentially empty space. Consequently, attenuation of generated particles in plasma lenses is minimal. Since the major component of a plasma lens is ionized gas, the bulk of the lens is impervious to radiation and thermal damage. Forty years ago, a 1.5-meter long, 40-cm diameter "Z-pinch" lens, with a current of 500 kA for 15μsec duration was successfully used in an AGS experiment. This lens performed very well until its ceramic liner broke and was not replaced since the experiment was close to its conclusion. Since then, various special Kevlar, fiberglass, and carbon epoxy liners and insulators have been developed for radiation generating machines (used in weapons research) that are durable under extremely intense radiation. Also, dramatic improvements in capacitors have occurred during the past twenty five years that resulted in a quantum jump in this important technology.

Although horn technology is mature and horns are reasonably suited to neutrino beam generation, plasma lenses have many advantages over horns that cover all seven points of an "ideal lens." As noted in the previous paragraph, plasma lenses are better than horns for each of the first five points. Since plasma lenses can capture negatively charged pions while deflecting positively charged pions with trajectories that are at very small angles to the target axis (unlike present horns), the neutrino signal can be minimized during anti-neutrino running (point 6). Presently (based on the use of horns), 15% of the beam signal is neutrinos during anti-neutrino runs (while; in case of neutrino run, anti-neutrinos constitute 4% of the signal). Finally on point 7, horns use more power and contain more material (cost more). As horns heat-up, their resistance (and power consumption) increases while the plasma resistance drops during the pulse (after 1 nsec Voltage drops from about 20 KV to a few Volts).

To summarize, very simple arguments have been invoked to support the R&D development of a plasma lens. A plasma column can be shaped (similar to a horn) and sustain larger currents to capture more pions without leaving a "hole" (field-free axial region at small angles) to yield larger cleaner neutrino (or anti-neutrino) signals. With the exception of the need for R&D investment, plasma lenses appear to offer significant advantages over horns in all the "ideal" lens characteristics. Horn technology has saturated with no conceptual advances reported in years, while plasma lenses have the potential for large improvements to accommodate an aggressive and productive future U.S. neutrino program.

A Novel Integrated Lens/Target for Pion Capture

We propose a 3-year, $600K R&D program in which a conceptual design, plus a low-duty-factor prototype, of a two-element, pinch-like focusing lens configuration will be produced. In the two pinch-like lenses, large axial currents will be carried by plasmas outside of and downstream of the solid carbon pion production target. The downstream plasma current channel can be magnetized and its profile easily shaped. The downstream lens will capture pions with small angle trajectories that would not be captured by a horn-based system and (important to anti-neutrino beams) defocus opposite-sign pions that produce unwanted backgrounds. A variation of this concept is to carry all or part of the target lens current through the target itself, utilizing high conductivity graphite like quasimonocrystal graphite.

For the first configuration of a combined lens/target configuration, current could be fed at some point downstream from the beginning of the target where pion capture is needed. The feed point could be varied *in situ* to optimize the resulting neutrino flux. The target would be followed by a plasma lens that carries additional current to provide a higher current in the plasma lens. The target section of the plasma lens could be immersed in an external solenoidal magnetic field to facilitate its current profile shaping. This current profile would be shaped to optimize pion capture. The issue to be tested is the effect of flowing current outside the target and/or inside the target itself. At current levels of 300 kA or less, the carbon target should not be affected by Z-pinch-like compression.

Driving current through the production target increases its heat load, already a serious issue from the proton beam heating. Room temperature resistance of a carbon target (based on present design) made of high conductivity graphite like quasimonocrystal graphite is about 6×10^{-3} Ohm at room temperature. Considering a worst case scenario of 300 kA through the target (horn's current is only 250 kA) for 3 μsec, the energy deposited in the target is about 1.7 kJ. By comparison, the proton energy deposited in the target per pulse is 7.3 kJ; therefore, the deposited electrical energy increases the target heat load by 23%. Reducing the current to 250 kA results in 1.18 kJ deposited (16% of beam energy deposition). Depending on simulation results, it is likely that the per-pulse electrical energy deposited in the target will be only a small fraction of the 1.7 kJ worst-case scenario. High conductivity graphite like quasimonocrystal graphite has a very nice property for this application, since its high electrical conductivity is in one direction only. But, the durability of this property under intense radiation must be tested.

During the first R&D year, simulations to determine the optimal plasma lens configuration will be performed, including comparisons to a horn-based system. Two sets of experiments will be conducted: a graphite test target in a Z-pinch; a high radiation exposure to test radiation damage effects on high-conductivity graphite.

In the second R&D year, an optimum design configuration would be developed, based on simulation and experimental results. This would be followed by experimentation and iterated design refinement to identify the optimized lens configuration.

In the third R&D year, a low duty factor prototype would be fabricated and test experiments performed.

Detailed R&D Plan and Budgets

The Principal Investigator (PI) for the project is Ady Hershcovitch of BNL. Our three-year R&D plan is based on programs the PI has carried out with collaborators in the Physics and Astronomy Department at the Univ. of California, Irvine (UCI) over the past seven years. The R&D Plan and costs are developed from the ongoing BNL-UCI Z-pinch ion source development program. Labor at UCI includes a doctoral student (with some supplementary pay to his faculty adviser as well as some UCI shop time); two UCI staff physicists would contribute to the work as consultants.

As a consequence of the ongoing Z-pinch ion source development program with UCI, there are facilities (pulsed power equipment, capacitor banks etc.) and a test stand at UCI that are particular suitable for the proposed R&D. UCI has the best university-based, non-defense program expertise in pulsed power technology. We provide here by fiscal year, R&D budget for this work by cost category and R&D task.

Task 5 Budget Line Item Cost Schedule by Cost Category

Budget item	FY06 ($K)	FY07 ($K)	FY08 ($K)	Total ($K)
BNL Personnel: PI, physicist, engineer & tech	90	77	63	230
UCI student cost (includes professor and other costs)	55	57	60	172
Materials and Supplies (mostly BNL, some UCI)	10	12	12	34
Contract work: UCI physicists as consultants	25	30	40	95
Travel and other costs (mostly shops at BNL)	20	24	25	69
Totals	**200**	**200**	**200**	**600**

All costs, except for BNL G&A and burdens, are included in the above budget (BNL Labor costs include the BNL paid absence burden and fringe). The BNL PI will direct and coordinated all R&D tasks to be performed. The following Table lists the R&D tasks and staff composition:

The effort costs comprise: the BNL PI @ 20% 1st year, 30% 2nd & 3rd year; the BNL simulation physicist @ 20% 1st year, 10% 2nd year; the BNL engineer @ 20% 1st year 10% 2nd & 3rd year; plus 1 UCI doctoral student (the only full-time person), 1 BNL technician very limited time (cost of no more than $2k - $3k per year), and 2 UCI consultants.

Task 5 R&D Budgets by Subtask and Fiscal Year

Task Description	**Performed by At Location**	**Budget item**	**FY06[a] ($K)**	**FY07[b] ($K)**	**FY08[c] ($K)**	**Total ($K)**
Simulations to determine optimum plasma lens configuration	PI & BNL Physicist At BNL	personnel	80			80
Effect of plasma pinch on graphite target	PI, UCI student & Professor, UCI consultants at UCI	personnel student cost consultants travel & shop mat. & supp.	85			85
Effect of prolonged radiation exposure on high conductivity graphite	PI & BNL engineer At BNL	personnel travel & shop mat. & supp.	25			25
Design of optimum plasma lens configuration	All participants at both BNL and UCI	personnel travel & shop		90		90
Experimentations and iterated design refinement	PI, UCI student & Professor, UCI consultant at UCI	personnel student cost consultants travel & shop mat. & supp		87		87
Fabrication (mostly at BNL shops) of full scale prototype; low duty factor experimentation	PI, UCI student & Professor, UCI consultants @ UCI	personnel student cost consultants travel & shop mat. & supp	10	23	200	233
Total			**200**	**200**	**200**	**600**

[a] FY 2006 – determine and design the optimum plasma lens configuration, plus simulate its neutrino generation performance including comparisons with horn-focused beams; the PI will direct the BNL physicist and engineer; experiments will be performed with carbon target in a Z-pinch; the PI will direct the UCI student and consultants; experiments will be performed for exposure of high-conductivity graphite to intense, prolonged radiation; the PI will direct the BNL engineer and technician.

[b] FY 2007 – design and experimentation with optimized lens configurations; iterated design refinements; the PI will direct the BNL physicist, BNL engineer, UCI student, and contract consultants.

[c] FY 2008 - fabrication & test experiments with the low duty factor prototype; the PI will direct UCI student, BNL engineer, and contract consultants.